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Perceptual Learning in the Acquisition of Flight Skills

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Many skills transfer effects observed in flight training research may be explained by an appeal to invariant perceptual properties of the task environment. If training in a simulator serves to enhance sensitivity to perceptual properties that are critical to flight performance, a high level of transfer will result. The theory forwarded here assumes that a relatively low-dimensional set of properties supports flight control. It is those properties that need not be represented accurately, or even at all. One implication of the approach outlined here is that the unquestioning pursuit of high fidelity is, in large part, wasted effort.

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PERCEPTUAL LEARNING IN THE ACQUISITION OF FLIGHT SKILLS

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INTRODUCTION

Skill transfer occurs when an individual is able to perform a task more easily as a result of having practiced another, different task. In aviation, the procedure of working towards certification in complex, high performance aircraft via early training in less complex and lower performance aircraft attests to an implicit belief in skill transfer. The effects of skill transfer pervade our lives. In all manner of tasks we attempt, we continually exploit skills, tactics and strategies initially learned with other tasks and in other contexts.

Transfer is both positive and high when there is minimal difficulty in transitioning from one system (task or context) to a new system. It should be noted however, that a claim of high, positive transfer assumes that individuals who had not had the benefits of experience with the early system would encounter considerable difficulty in their adaptation to the new system. In essence, it should be possible to demonstrate a noticeable benefit from prior training on the early system.

Within any training environment, high positive transfer should be the goal. For aviation, a central issue in the design and use of flight training simulators is maximization of transfer. How should a simulator be designed so that there will be maximum transfer to the aircraft, and what types of instructional strategies can enhance transfer? There is also a concern that simulators not be fitted with costly options that do not enhance transfer.

SIMILARITY

The most pervasive notion employed in theoretical conceptions of transfer is that of similarity. To the extent that two tasks are similar, transfer will be high. Nevertheless, the conceptions of similarity that have been employed in theoretical formulations have not served the aviation community well. Similarity is often viewed quantitatively; the more there is of it, no matter on what dimension, the better transfer will be. Clearly, many dimensions of similarity are irrelevant to the transfer of flight skills; the color of the aircraft and simulator being just one. More importantly, there are dimensions of similarity that, on casual analysis, would seem to be critical. Simulator motion is one such dimension. Nevertheless, research has failed to show any transfer enhancement resulting from the use of a motion system during training (Lintern, 1987). It would appear that this dimension of similarity contributes nothing to the transfer of flight skills.

Another common approach to transfer is to incorporate a term that is intended to characterize the critical similarities. Identical elements (Thorndike, 1903), psychological fidelity (Goldstein, 1986), and functional equivalence (Baudhuin, 1987) constitute approaches which recognize that not all dimensions of similarity contribute to transfer. The common failing of these approaches is that the separation of important from unimportant similarities can only be accomplished on the basis of observed empirical trends. For example, does simulator motion constitute a functionally equivalent dimension? There is nothing in the characterization of functional equivalence that suggests an answer. In fact, these terms constitute no useful advance beyond the obvious truth that some similarities contribute to transfer and some do not. The challenge remains to establish a conception of

similarity that will advance our understanding of transfer and that will lead to accurate predictions of transfer effects.

DISSIMILARITY

A number of training studies have demonstrated that transfer to a target environment or task can often be better following training on a reduced context or task, where the comparison is made to training on a task that is more like, or even identical to the target environment or task (Lintern, 1991). In some sense, a lesser degree of similarity results in better transfer. One possible interpretation of such data is that the shedding of distracting or irrelevant similarities in the reduced task encourages trainees to focus attention on critical similarities so that important relationships are clarified. From this perspective, transfer from the reduced task is enhanced because of better skill with the critical similarities.

For example, Lintern, Roscoe, and Sivier (1990) and Lintern and Garrison (1992) have found that lineup in the approach to a simulated runway is better in transfer to a crosswind condition following training with no crosswind versus training with crosswind (Figure 1). This result is clearly counter to the fidelity view of transfer which implies that training for challenging environmental conditions is best accomplished under a close representation of those conditions. It is of interest to note that the advantage for training without crosswind was found only if the roll response was not changed between the training and transfer phases of the experiment (Lintern et al., 1990). One possible interpretation of this interaction is that without crosswind in training, students could more effectively learn the control-display relationships associated with the roll response of the simulation. Enhanced skill with these control-display relationships might assist adaptation to the

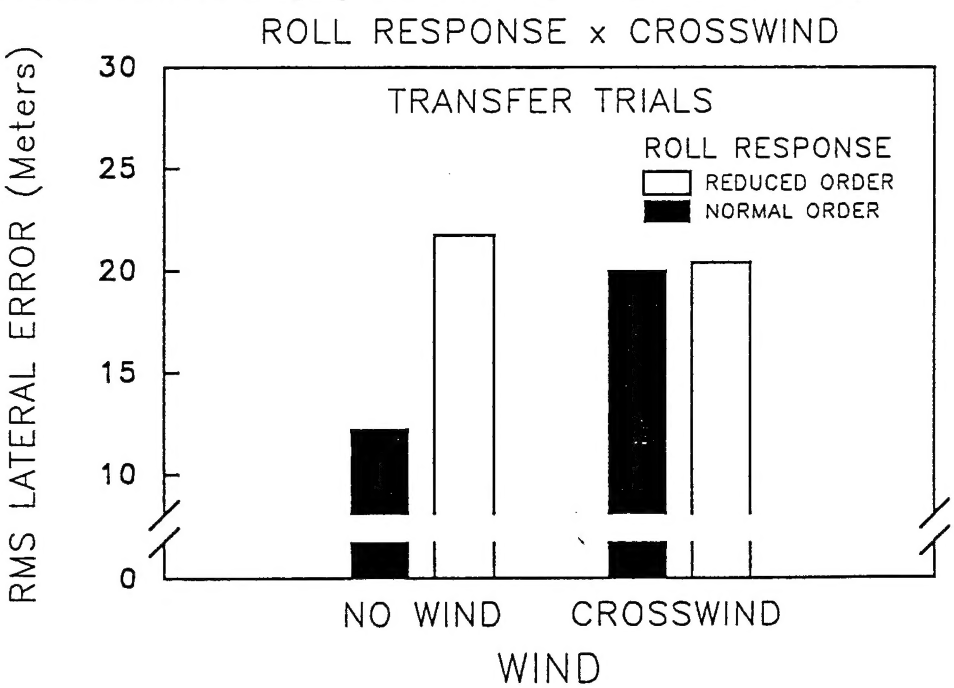

Figure 1. Line-up control interaction between wind conditions and roll response for simulated landing approaches (adapted from Lintern et al., 1990).

crosswind when it was introduced. Of course, no such advantage could accrue if the control-display relationships were changed at the time the crosswind was introduced.

INFORMATION FOR CONTROL

J.J. Gibson (1979) argued that human action (e.g., manipulation, stance, locomotion) is coordinated with perceptual information that specifies the state of the surround (i.e., an actor's environment) and the relationship (and the changing relationship) of an actor to the environment. A source of information for control of action is characterized as an invariant, which is a property that remains unchanged (within the limits of perceptual thresholds) if the actor executes a task correctly. Essential to the concept of an invariant is that the property will undergo a perceptible transformation if the actor strays from the limits of the task goal. Essentially, Gibson's claim is that informational invariants are critical to the execution of goal-directed behavior. One important goal of the scientific agenda outlined by Gibson is to identify and to classify invariants.

INFORMATION FOR FLIGHT CONTROL

Langewiesche (1944) proposed that pilots control the angle of a landing approach to the runway aimpoint by reference to the H-distance, which is the distance between the horizon and the aimpoint, projected onto a plane in front of the pilot and perpendicular to the line of sight (Figure 2). Lintern and Liu (1991) have recast the notion of H-distance as the H-angle (the angle between the line of sight to the horizon and the line of sight to the runway aimpoint). They have shown that distortions of the H-angle effected by

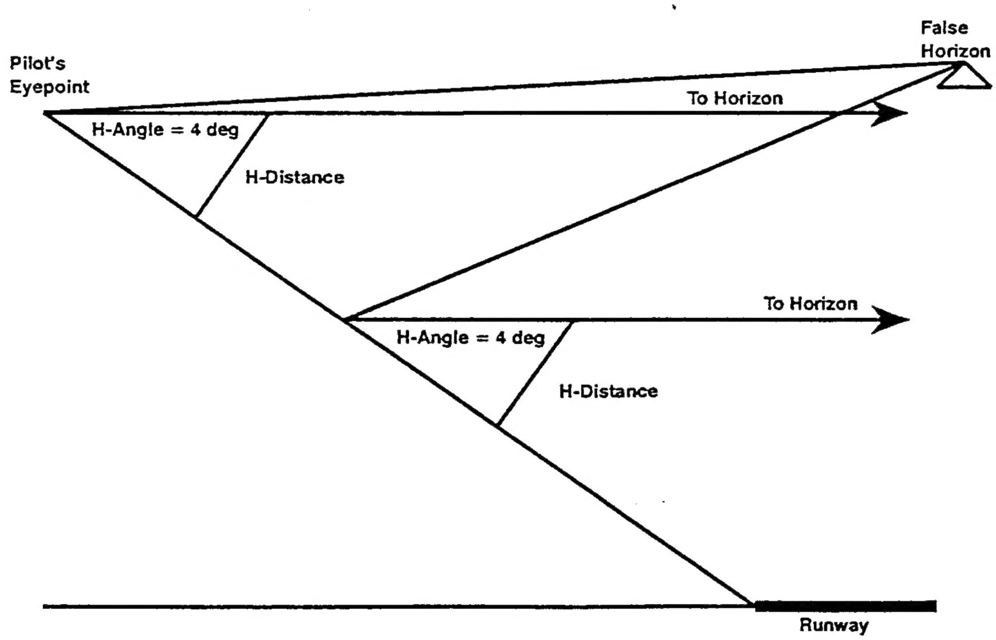

Figure 2. The H-distance and the H-angle remain invariant for a constant angle of approach. Also depicted is a change in H-angle induced by a "high" horizon (adapted from Lintern & Liu, 1991).

raising or lowering the visible horizon, have predictable biasing effects on the approach angle (Figure 3). Evident from the data in Figure 3 is that a horizon specified implicitly by a terrain gradient (Figure 4) can also impact behavior. One implication of this work is that pilots maintain a constant angle of approach by controlling the H-angle (cf. Powers, 1978); that is, they maneuver the aircraft to keep the H-angle at its desired value. Another implication of this working that the H-angle might be specified explicitly with a visible horizon or implicitly with a terrain gradient.

Gibson, Olum, and Rosenblatt (1955) have argued that pilots use the center of optic outflow to guide themselves towards the runway aimpoint. It would, however, be wrong to treat the optic outflow hypothesis as incompatible to or mutually exclusive of the H-angle hypothesis. Lintern and Liu (1991) demonstrated that more than one visual property influences glideslope control. Other experiments have demonstrated that deletion of ground detail from a simulated visual scene affects the bias and stability of a landing approach (Lintern & Koonce, 1991; Lintern & Walker, 1991). The optic outflow hypothesis provides one plausible account of these effects.

LEARNING AS DIFFERENTIATION

In the discussion so far I have advanced claims about the nature of what is learned during acquisition of an action skill but have referred only tangentially to the learning process. A theory of transfer must accommodate the fact that good transfer is achieved even though many things change in the transition from the training to the operational system. Within the gross changes between training and transfer, a low-dimensional set of critical relationships remains unchanged. From the informational perspective it is assumed that sensitivity to invariant properties such as the H-angle or the center of optic outflow is enhanced during training, and that improved skill with these properties leads to better transfer. A view of learning consistent with the informational perspective is that of perceptual differentiation; a process by which information becomes more discriminable (E.J. Gibson, 1969). In that it is a process whereby what was once perceived as the same is now perceived as different, there is an analogy to cellular biology where differentiation refers to the process by which formerly identical cells acquire unique characteristics.

Perceptual thresholds are central to any theory of perception based on invariants because, without reference to thresholds, there is no reference to the capabilities of the actor (Cutting, 1986). An actor must be able to perceive changes in perceptual information that is to be held invariant during execution of a task, and the concept of threshold is employed to account for the fact that the perceptual resolution of such changes is finite. The perceptual differentiation hypothesis implies that an actor's difference thresholds for recognition of changes or patterns in the workspace can be lowered through experience. There is a progressive development of the actor's sensitivity to constancies within tasks and differences between them. Learning moves through a course of progressively finer discriminations of important information, and regularities become informative via processes leading to differentiation along dimensions of variation. Previously vague impressions become increasingly specific as they relate to task requirements. From this perspective, skilled behavior must exploit perceptual information, and skill develops via a process of becoming sensitive to it.

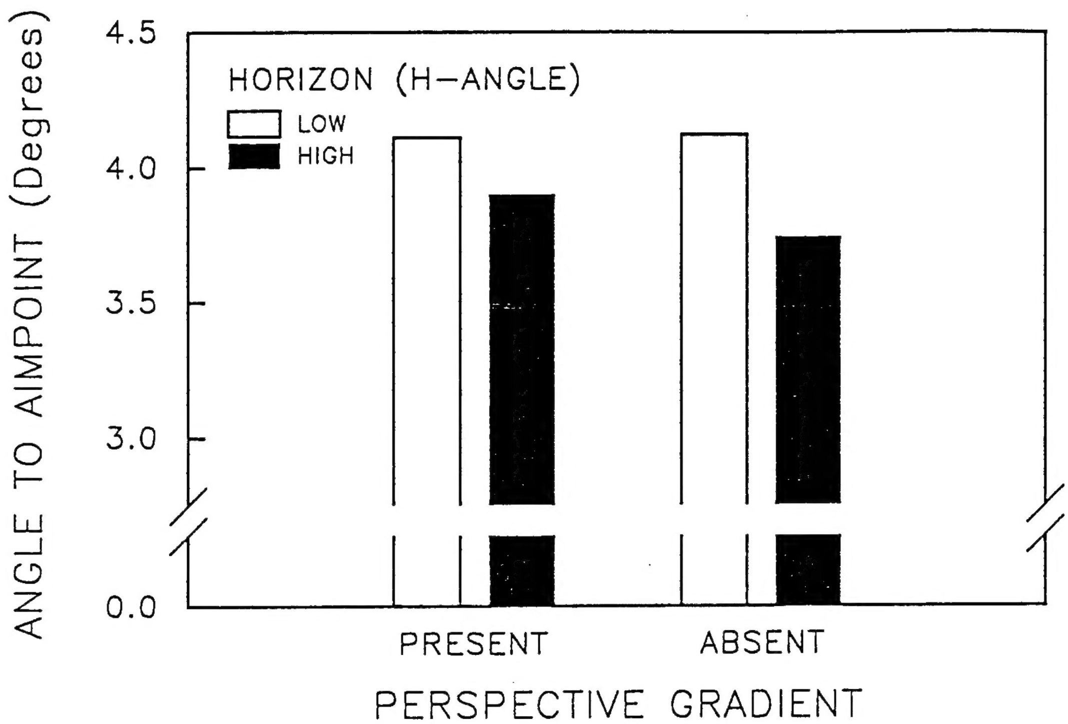

Figure 3. Interaction of approach angle means across changes in the H-angle and perspective gradient (adapted from Lintern & Liu, 1991).

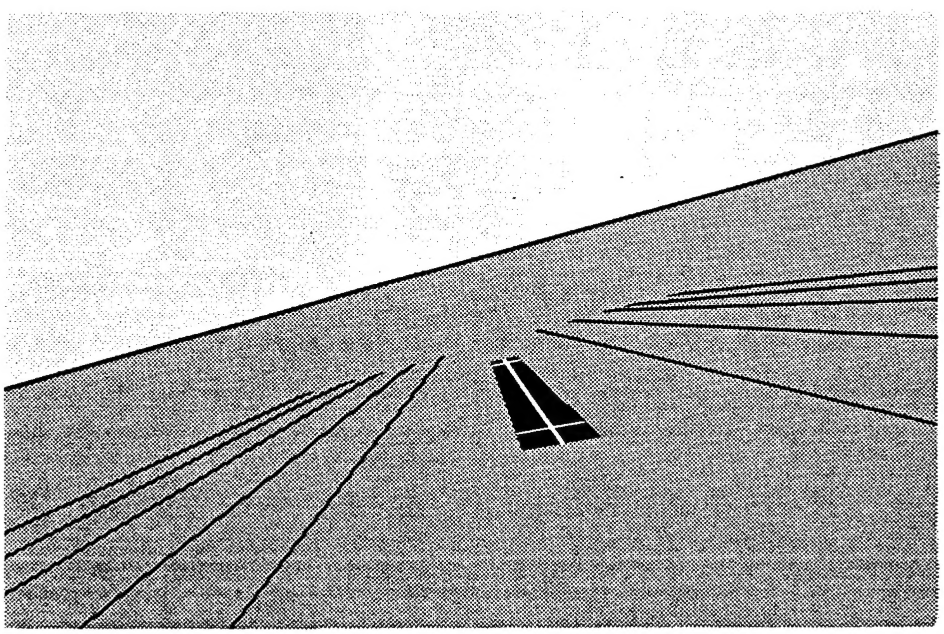

Figure 4. Black and white representation of an airport scene with the addition of perspective gradient lines that implicitly specify a veridical horizon (adapted from Lintern & Liu, 1991).

In her discussion of differentiation, Gibson (1969) emphasizes objects and events in the environment external to the observer. At the human-machine interface there is a wider range of concerns. Here learning will involve the increasing differentiation of previously confusable information which may reside in any element of the task environment, even in response production. The difference between skilled and unskilled behavior can therefore be at least partially characterized as differential sensitivity to task-related information.

Gibson's (1969) review suggests that certain instructional techniques can speed differentiation; in particular those that draw attention to the distinguishing perceptual invariants. Techniques that contrast different values of distinguishing properties, that abstract them, or that accentuate them should be useful. In some cases it may help to offer advice about what to look for (Biederman & Shiffrar, 1987). Nevertheless, even highly skilled actors are often unaware of the information they use to support their own activities and is unlikely that much of the information for skilled activity is sufficiently explicit for that type of instruction. Implicit information might be learned more readily via special instructional techniques that enhance or clarify it. Additionally, anything that diverts attention from, or conceals critical information will impede the differentiation process.

INCREMENTAL TRANSFER

Transfer refers to an enhancement of performance from prior experience with a different task. Incremental transfer refers to the comparative effects on performance of prior experience with one of two or more available tasks. For example, a relative performance advantage in an airplane that results from prior training in one versus another type of simulator is referred to as incremental transfer. The study of incremental transfer is important to flight simulation because it provides a means of assessing the relative training effectiveness of different simulator configurations and instructional options. In our own research program we have found incremental transfer effects following variations in visual displays, instructional features, dynamical response, and environmental conditions (Lintern et al., 1990; Lintern & Garrison, 1992; Lintern & Koonce, in press; Taylor, Lintern, Koonce, Kaiser, & Morrison, 1991).

This program of research was planned to develop principles of design and of use for flight simulators. However, the pattern of effects has turned out to be more complex than anticipated. In a recent experiment (Lintern & Koonce, in press) both guidance and command forms of augmentation were tested (Figure 5). A final approach to landing was taught to beginning flight students. Guidance augmentation (the facing F bars in Figure 5) showed the optimum glideslope to the runway aimpoint, and command augmentation (the airplane symbol in Figure 5) showed the commanded course and roll of the simulated aircraft. Both constant and adaptive modes of augmentation were compared to no augmentation during training. In the adaptive mode the augmentation switched on only when the student departed from an optimum flight envelope. This led to the adaptive augmentation being automatically withdrawn (or faded) as the student became more skilled.

Earlier research into augmented feedback had suggested a dependency principle; that is any special instructional procedure should not encourage

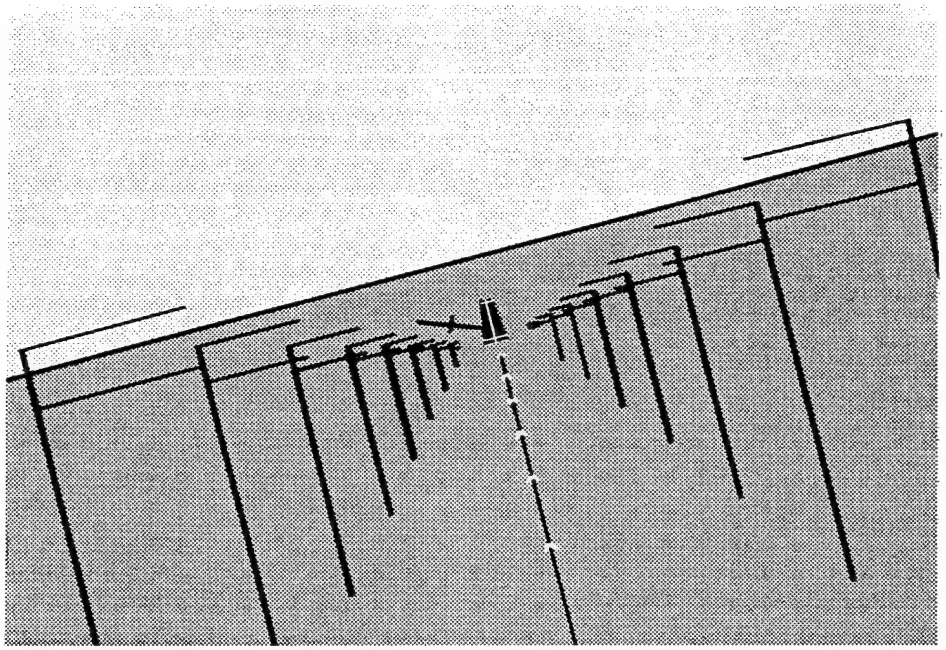

Figure 5. Black and white representation of a low-detail airport scene with guidance augmentation F poles and a command augmentation airplane symbol (adapted from Lintern & Koonce, in press).

dependency on information or other assistance that is not available in transfer (Lintern, 1980). Both constant and adaptive augmentation had induced excellent performance during training but, in transfer when all augmentation was withdrawn, those trained with constant augmentation performed only as well as subjects trained with no augmentation, while those trained with adaptive augmentation maintained their excellent level of performance. The same pattern of results was found by Lintern and Koonce (in press) for command augmentation (Figure 6) but not for guidance augmentation (Figure 7). Thus, the dependency principle does not provide a consistent account of diverse trends found by Lintern and Koonce (in press).

A central challenge for our research program is to account for these diverse differential transfer effects. From the informational perspective it is assumed that different training manipulations direct attention to different informational invariants. Although it is possible to generate hypotheses about the causes of the difference, it is first important to establish the basic proposal. The strategy is to insert probe trials into the transfer phase following training manipulations that have produced differential transfer effects in prior experiments. Informational properties that are known to support flight control are selectively distorted or deleted in the probe trials. If differential sensitivity to those properties has been developed, the probe distortions or deletions will have predictable differential effects.

One experiment of this type has been conducted so far. Reisweber and Lintern (1991) taught simulated landings to flight students in a multifactor quasi-transfer experiment. Command augmentation was manipulated as one of the training variables. Probe trials, in which a perspective gradient was either

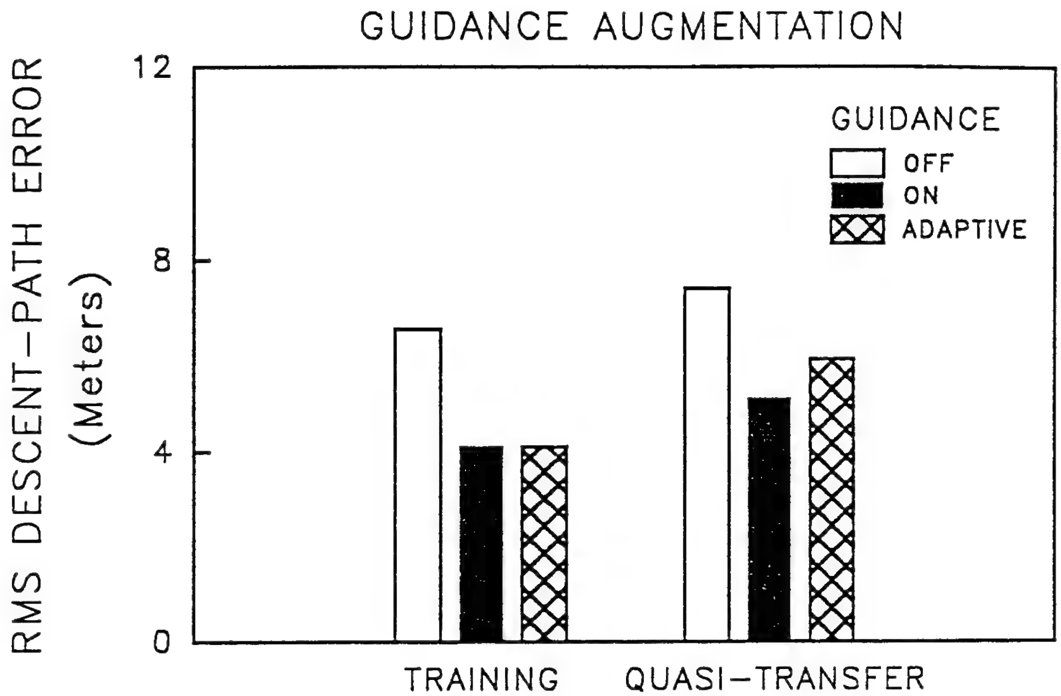

Figure 6. RMS descent path error in training and quasi transfer for training with guidance augmentation (adapted from Lintern & Koonce, in press).

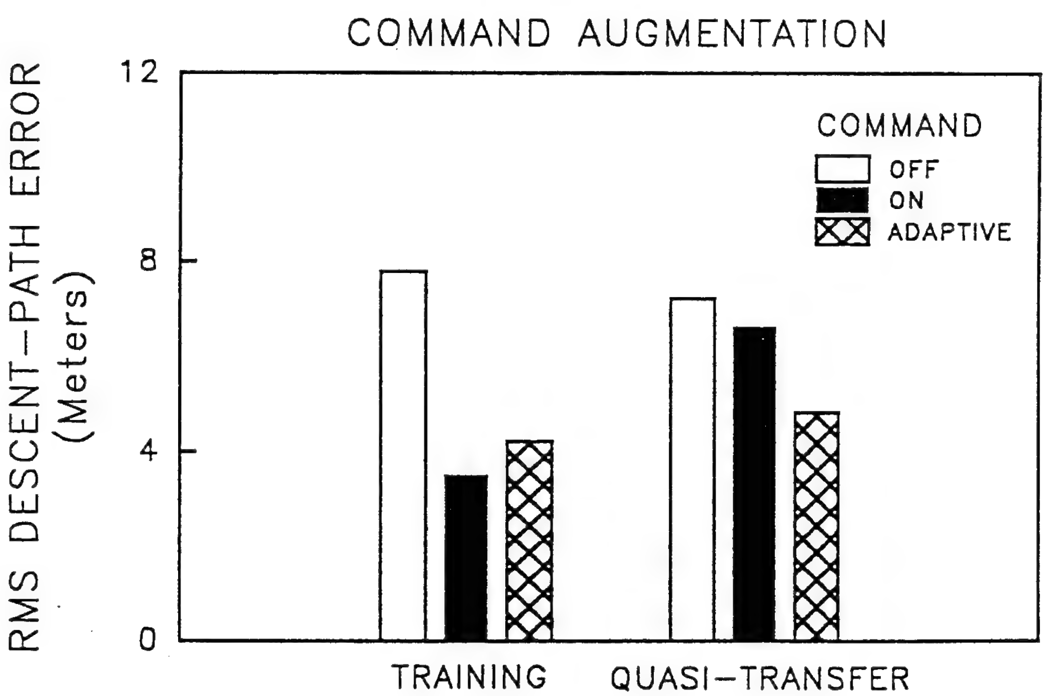

Figure 7. RMS descent path error in training and quasi transfer for training with command augmentation (adapted from Lintern & Koonce, in press).

present or absent and the visible horizon was either high or low (cf. Lintern & Liu, 1991) were inserted into the transfer phase.

The data of Figure 8 show how the presence or absence of perspective gradient in the probe trials differentially influenced the descent path bias of those trained with constant, adaptive, or no command augmentation. Specifically, those trained with adaptive command augmentation were not influenced by the presence or absence of the perspective gradient. Those trained with constant or with no command augmentation flew lower in the absence of perspective gradient as is consistent with Lintern and Liu (1991) for data from qualified pilots. Thus, training with no command augmentation or constant command augmentation appeared to enhance sensitivity to the perspective gradient information, while training with adaptive command augmentation did not. There is much that remains to be resolved, but the results of this experiment provide considerable encouragement that the causes of complex differential transfer effects might eventually be identified in the differential sensitivity developed to invariant perceptual properties.

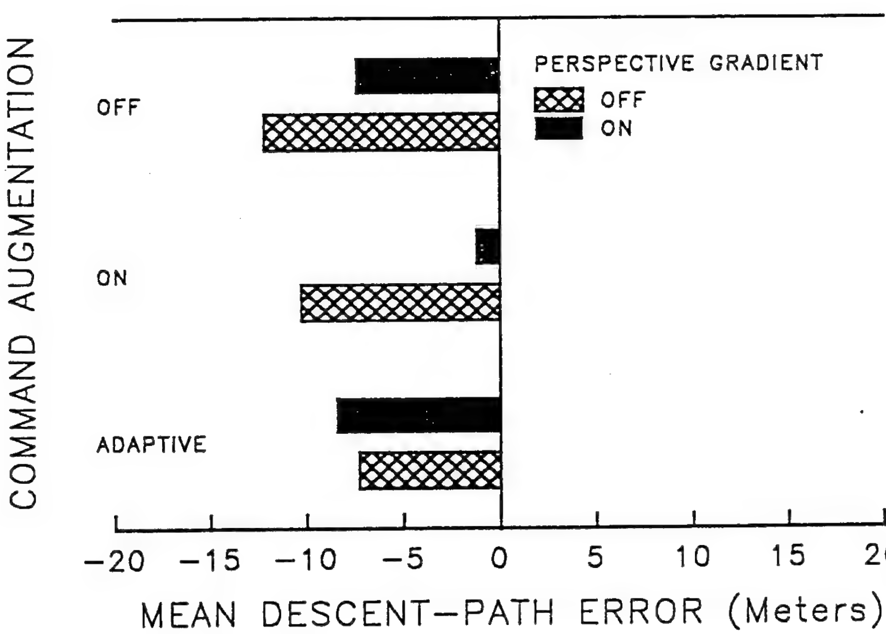

Figure 8. Mean descent path error following training with command augmentation in probe trials in which a perspective gradient was either present or absent (adapted from Reisweber & Lintern, 1991).

DISCUSSION

The informational account offered here is, to my knowledge, the first synthesis of transfer effects which show better transfer following training on a task that differs in some specific respects to the criterion task than following equivalent training on the criterion task itself. From an identical elements perspective (Thorndike, 1903), an instance memory perspective (Logan, 1988), or a response versus stimulus similarity perspective (Holding, 1976), trends of this type must be viewed as atypical. In contrast, the appeal to informational invariants forms a basis for a detailed characterization of the

task and, when combined with the differentiation hypothesis, one which provides a theoretical account within which many puzzling transfer data become explicable.

The development of a coherent account of skill transfer has proved to be a struggle throughout the past century of psychological and educational research. Commencing with the notion of formal discipline (Woodrow, 1927), a variety of views have emerged, none of which has been able to provide an account that offers a clear research agenda or comprehensive training principles. Major training research programs are sometimes planned under the explicit assumption that contemporary theory should be ignored (e.g., Donchin, 1989). At other times, research programs are built around such limited tasks that their relevance to common human activity is questionable (e.g., Logan, 1988). Reviews of transfer research tend to emphasize behavioral outcomes and also to lament obvious deficiencies, but offer little by way of solid theoretical integration (e.g., Baldwin & Ford, 1988; Briggs, 1969; Lintern & Gopher, 1978; Wightman & Lintern, 1985). The account forwarded here constitutes an attempt to resolve these problems. Although the emphasis has been on transfer in flight control, J.J. Gibson's ecological theory is posed as an account of normal human activity. Thus, the informational perspective should be relevant to issues of skill transfer with all types of human-machine systems that are of concern in the field of Human Factors.

Invariants as a Basis for Transfer

The central claim forwarded in this paper is that transfer can occur only where critical similarities are maintained across the training and transfer tasks. I have argued that informational invariants constitute the properties that define the critical similarities and that they are essential components of all tasks that can be learned. If critical invariants (specifically, those that pose a meaningful learning challenge) remain unchanged, transfer will be high even where many other features of the environment, context, or task are changed. The learning aspect of this theory was described in terms of differentiation; a process whereby perceptual thresholds are modified. If an operator's perceptual sensitivity to critical invariants can be improved, that enhanced sensitivity will serve to facilitate transfer. A basic assumption of this discussion is that initial contact with any unnatural control environment will almost invariably require the development of sensitivity to new invariants.

Following E.J. Gibson (1969), procedures that accentuate invariants to be learned will enhance differentiation. Thus, clarification or enhancement of invariants that offer a significant learning challenge will speed skill acquisition. The concealment or distortion during training of those critical invariants should actually impede learning. On the other hand, emphasis on invariants that are already well learned, that are easily learned, or that are nonfunctional will not impact transfer.

Transfer Theory

There are points of contact with other theories, but one implication of the informational account outlined here is that other attempts to account for transfer of skill through an appeal to some conception of similarity are either incomplete or inadequate. This account shares with Logan's (1988)

instance memory theory a concern with information from an actor's environment, but differs in its emphasis on low-dimensional properties of that environment. It also has something of the character of the response surfaces developed by Osgood (1949) and Holding (1976) but offers a different conceptualization of the task features that must be considered.

In that it could be viewed as an account of the information that is internalized as a motor program or a rule, this informational theory might be seen to complement internal process theories, such as the rule-based approach of Gick and Holyoak (1987) or the motor-program approach of Schmidt and Young (1987). That view is not, however, consistent with the ecological program of J.J. Gibson (1979). From the ecological perspective, an appeal to rules or motor programs adds nothing in the way of explanatory power and constitutes little more than an alternate description (Lintern & Kugler, 1991) of observable properties in behavior or in the environment. Such an appeal does not offer a more parsimonious, more general, or more fundamental description; nor does it offer an explanation (Gibson, 1973, 1976).

Nevertheless, some form of change or reorganization, internal to the actor, is accomplished during learning. A clear understanding of that change or reorganization would, in all likelihood, contribute considerably to our understanding of skill transfer. There is, however, no consensus within behavioral science about how to characterize that change or even about the scientific strategy that is most likely to reveal it. The most common strategy, to postulate a hypothetical construct that appears to account for important data trends, raises a serious difficulty for a theory of transfer. While implications for transfer can be drawn from a hypothetical construct, failure to find the anticipated effects can be accommodated by adjustment of the theoretical formulation. As is evident within the general field of cognitive psychology, there are endless variations on hypothetical constructs that can be forwarded to account for diverse effects.

In the current context, the ecological critique amounts to a claim that an internal process, if rigorously specified, will be defined in terms of objective informational properties to be found in the actor-task environment. In that case, the postulated internal process adds nothing useful to the informational account. A less rigorous specification of internal process will rely heavily on hypothetical constructs that cannot be evaluated directly and that provide nothing in the way of compelling predictions. Circularity becomes a significant problem in that a transfer construct (e.g., functional equivalence, motor program) can be specified only in terms of behavioral data that the construct is presumed to explain.

In contrast, information is derived from real properties in the task environment. Those properties can be measured objectively and can be distorted, enhanced, or removed. An appropriate task analysis should reveal the relevant informational invariants and should provide specific predictions relating to the effects of adjusting that information. Gibson's ecological program places a heavy burden on the scientist to identify the informational properties that impact behavior. For transfer theory, specification of informational invariants that support transfer is a central requirement. From the ecological perspective, success in that regard will provide considerably more insight into the complexities of skill transfer than any amount of theorizing about internal process or structure.

Transfer Research

There has been considerable confusion about transfer because experiments that should seemingly be able to demonstrate it often do not. There is generally only a vague notion of what can be transferred and what might promote that transfer. The informational perspective suggests a strategy that should correct this unsatisfactory situation. In terms of this perspective it should be possible to specify by analysis the information that is expected to support transfer. It should then be possible to demonstrate predictable performance effects of distorting or of concealing that information and to demonstrate predictable effects on transfer of specialized pretraining with that information in isolation or of pretraining on the whole task with that information distorted or concealed.

Specifically, for a task such as landing a light aircraft, it should be possible to identify structural relationships in the environment that specify whether or not the pilot is maintaining correct lineup and glideslope. The horizon-aimpoint angle is one such invariant property that is used to maintain glideslope control (Lintern & Liu, 1991). It should also be possible to identify dynamic relationships within the flight control system that specify whether or not the pilot has stable control over the aircraft. Speed of system response to control inputs is likely to incorporate one invariant relationship critical for transfer (Lintern & Garrison, 1992). Beginning flight students may already be sensitive to some important invariants but if the task poses a significant learning challenge there will be at least some invariants that are not perceived well and sensitivity to them will have to be enhanced through instruction and practice. It is those invariants that must be identified and assessed in terms of their impact on transfer. More generally, the challenge for transfer research is to identify informational invariants by analysis, to demonstrate their impact on behavior, and to assess their effects on transfer.

Issues for Applied Training

It should be apparent, from consideration of the data reviewed in this paper, that the development of a training system requires a detailed analysis of the tasks to be learned. As a first step, invariant relationships that support transfer must be identified and must be faithfully reproduced in a training system. In the design of a flight simulator, for example, faithful representation of the horizon-aimpoint angle may be critical (Lintern & Liu, 1991). It is not uncommon however, especially where inexpensive computers are used for the generation of a visual display, to model a relatively small world. That results in a distorted horizon-aimpoint angle which does not remain invariant for a constant angle of a landing approach and, by the perspective offered here, is likely to compromise transfer effectiveness.

In that we know little about invariants that support behavior nothing presented in the development of this theory should be taken as implying that identification of relevant informational invariants is straightforward. The few data that have emerged from research stimulated by Gibson's ecological program indicate that invariants will be based in abstract relationships (Lintern & Liu, 1991; Mark, 1987; Warren & Whang, 1987). The results of the biological motion research (Cutting, Profitt, & Kozlowski, 1978) suggest that

invariants will be discovered in unexpected forms; in particular ones that are not well anticipated by the bulk of the traditional research into perceptual issues. Identification of critical perceptual invariants is likely to pose a continuing challenge for designers of instructional programs and devices.

Once the relevant invariants have been identified and represented appropriately in the training system, a second step is to implement instructional strategies that will speed their learning. There is at least some indication in the research discussed here of the types of instructional principles that could be useful. From the review of E.J. Gibson (1969), clarification and accentuation seem to be important principles. It will, however, require careful evaluation to verify that these types of strategies can be extended to a diversity of complex tasks, and to tune them for maximum effectiveness in specific circumstances. Thus considerable work remains before the implications of this theory can be readily transferred to operational training. Nevertheless, the promise is that a systematic development of the concepts presented here can, in the long term, have a substantial impact on training effectiveness.

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APPENDIX

Work completed under ARI contract MDA 903-86-C-0169: "Perceptual learning in the acquisition of flight skills."

Theoretical Papers

Lintern, G. (1991 a). An informational perspective on skill transfer in human-machine systems. Human Factors, 33, 251-266.

Lintern, G., & Kugler, P.N. (1991). Self organization in connectionist models: Associative memory, dissipative structures, and Thermodynamic Law. Human Movement Science, 10, 447-483.

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Lintern, G. (1991 b). Instructional strategies. In J.E. Morrison (Ed.), Training for performance: Principles of applied human learning (pp. 167-191). John Wiley & Sons.

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Synopsis

A paper describing the main theoretical perspective underlying this work has been published (Lintern, 1991 a). Other features of the theoretical perspective are outlined in Flach, Lintern, and Larish (1990), and in Lintern (1991 b).

The nature of the informational properties that support an approach to landing has been explored in three experiments. The first two (Lintern & Koonce, 1991; Lintern & Walker, 1991) laid the groundwork for the third (Lintern & Liu, 1991) where it was demonstrated that the horizon-aimpoint angle was one important informational invariant for approach control. The results of this experiment also showed that both explicit and implicit specifications of the horizon could enter into the horizon-aimpoint relationship. In addition, it became clear that the horizon-aimpoint angle is not the only informational property that is used in approach control. Others that are as yet not clearly identified also have a role to play. Work is continuing to identify the remaining informational invariants.

Three transfer experiments have also been completed. One tested the effects of scene content and augmented guidance on the acquisition of descent path control skill (Lintern & Koonce, in press). Another examined the effects of manipulations in crosswind strength and scene content on the acquisition of approach lineup skills (Lintern & Garrison, 1992). The results of these experiments are generally consistent with the view that clarification of informational properties during training can lead to better transfer.

There were, however, some puzzling transfer effects for visual augmentation used in training (Lintern & Koonce, in press). It appears that some forms of augmentation direct attention predominantly to one informational property while other forms of augmentation direct attention to another informational property. The third transfer experiment (Reisweber & Lintern, 1991) demonstrated that sensitivity to the H-angle identified by Lintern and Liu (1991) is enhanced by one form of augmentation while sensitivity to other, as yet unidentified properties, is enhanced by other forms of augmentation. This most recent transfer experiment has validated an experimental procedure that can be used to establish the significance of specific invariants to skill transfer.

In summary, the hypothesis about the role of invariants in the performance of manual control tasks and in skill transfer was, at the start of this project, a speculative extension of Gibson's (1979) ecological theory and was without empirical support. This project has led to the accumulation of some critical empirical evidence. We have demonstrated that invariants in support of manual control can be isolated, and that many puzzling transfer effects can be explained within the informational framework. The application of perceptual learning principles to manual control has also gained considerable empirical validation.